

NAVAL WAR COLLEGE
Newport, Rhode Island

COMPLETING THE SENSOR GRID: A REVOLUTION IN IMAGERY
MANAGEMENT

by

Mark W. Spivey
National Imagery and Mapping Agency

A paper submitted to the faculty of the Naval War College in partial satisfaction of the requirements of the Department of Joint Military Operations.

The contents of this paper reflect my own personal views and are not necessarily endorsed by the Naval War College or the Department of the Navy.

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5 February 1999

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Operation Desert Storm, Desert Fox and Deliberate Force (Serbia) all demonstrate that the military is in the process of a paradigm shift related to targeting. The improved accuracy of weapons is leading Operational Commanders to use almost exclusively Precision Guided Munitions (PGMs) that cannot function without a large volume of highly accurate target coordinates. In response to a Defense Science Board recommendation, the National Imagery and Mapping Agency (NIMA) has begun the development of a global set of geospatial information using satellite imagery as the base. If we are to respond decisively and maintain the initiative in evolving conflicts we need both a large volume of precise points complemented by quick access to targeting imagery. Such an imagery database (Sensor Grid) does not currently exist, but investigations internal to NIMA indicate that modifications to imagery management and triangulation have the potential to revolutionize the availability of Mapping, Charting, and Geodesy (MC&G) imagery. This paper will examine the imagery management practices that must change in order to make it feasible to develop a world-wide database of satellite imagery so that the PGMs of the future may be as responsive as they are accurate.

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INTRODUCTION

No negotiations can be conducted, no forces can move, no weapons can be brought to bear, no forces can be protected, and no support and supplies can move without a sense of location, an understanding of surroundings, and an understanding of the influence of mission space on the operation.¹

Joint Vision 2010 highlights that dominant maneuver, precision engagement, full dimensional protection, and focused logistics all depend on information superiority.² Recognizing that imagery and imagery-based intelligence under-pin global engagement, the Defense Science Board (DSB) recommended in 1995 that the Department of Defense evolve a distributed, heterogeneous, Internet-like architecture that uses geospatial databases as its foundation.³ Geospatial information is any data that represents cultural or land features referenced to an accepted coordinate system.

In response to the DSB's recommendation, the National Imagery and Mapping Agency (NIMA) has begun the development of a global set of geospatial information to serve as a foundation which can then be tailored to specific mission requirements.⁴ The base of geospatial data now, and in the foreseeable future, will continue to be satellite imagery containing precise positioning parameters needed for targeting and reference.⁵

Operation Desert Storm, Desert Fox and Deliberate Force (Serbia) all demonstrate that the military is in the process of a paradigm shift related to targeting. The improved accuracy of weapons is leading Operational Commanders to use almost exclusively Precision Guided Munitions (PGM) or Bomb-on-Coordinate weapon systems. These systems cannot function without a large volume of highly accurate target coordinates.

Indeed, if we are to respond decisively and maintain the initiative in evolving conflicts, we need both a large volume of precise points complemented by quick access to targeting imagery.

The challenge is to complete a world-wide database ("Grid") of imagery that can be accessed for precise positioning at a moment's notice. Such a database does not currently exist, but there are some signs of hope. Investigations internal to the National Imagery and Mapping Agency indicate that modifications to imagery management -- in conjunction with presently funded Geospatial Information Systems -- have the potential to revolutionize the availability of Mapping, Charting and Geodesy (MC&G) imagery.⁶ This MC&G satellite imagery could efficiently construct a global sensor grid, allowing the PGMs of the future to be as responsive as they are accurate.

This paper will examine imagery management practices that must change in order to make it feasible to develop a world-wide database of satellite imagery. Specifically, eliminating the 'boxing' of imagery into 60X60 nautical mile rectangles coupled with a redesign of the triangulation process has the potential to eliminate backlog, save time, and more importantly result in total exploitation of currently available imagery for targeting and the creation of Mission Specific Data Sets (MSDS). The imagery acceptance and triangulation processes within NIMA must evolve to keep pace with increased collection capacity and the targeting demands of global engagement against sophisticated adversaries.

I. TARGETING IN 2010

To fully realize the aim of an entire fleet of combat aircraft capable of launching large numbers of autonomously guided, accurate munitions, the Air Force must have a timely supply of accurate target coordinates.⁷

Joint Vision 2010 describes Precision Engagement as a system of systems that will enable our forces to locate the target, provide responsive command and control, generate the desired effect and maintain the flexibility to re-engage with precision when required. Of all the components of JV2010, Precision Engagement most specifically applies to target point positioning. Precision engagement means that our forces will be able to find and accurately geo-position targets as well as maintain command and control with the full knowledge of where our forces are within the operational space.

Our National Security Strategy and National Military Strategy plans for the sustainment of two major regional crisis along with the JV2010 concept of Global Engagement dramatically highlight the need for a more complete system of targeting support data. Against large adversaries, the simultaneous identification and targeting of thousands of critical vulnerabilities may be required.⁸ PGM planners have pre-measured scores of potential targets; however, no planning during peacetime can accurately predict each specific objective to be targeted during the next conflict. In fact, the target lists generated prior to conflicts are composed mainly of generic sites that need refinement based on intelligence or which are subject to change altogether depending on mission objectives.

Operation Desert Fox (Dec. 1998) demonstrated that a transition from the man-in-the-loop, mostly visual target acquisition process, to a preference for standoff, bomb-on-

coordinate, Global Positioning System (GPS)-aided munitions has already occurred. Already deployed in increasing numbers, the precision planning needed by these weapons cannot be done without the targeting support of national and theater agencies.

Upon its formation, in October 1997, Congress gave the National Imagery and Mapping Agency (NIMA) the responsibility for imagery requirements management, for tasking of imagery collection, for coordinating image processing and exploitation, and for ensuring image dissemination and archiving.^{9,10} Clearly, NIMA's development of geospatial information must include the ability to accurately and quickly exploit satellite imagery to support the weapons of the future.

EMERGING GPS-AIDED MUNITIONS

* GPS-aided Munitions (GAM)	Already on B2
* Joint Direct Attack Munitions (JDAM)	IOC: FY98
* Joint Air-to-Surface Standoff Missile (JASSM)	IOC: FY01
* Conventional Air Launched Cruise Missile (CALCM)	Flight tested Dec. '96
* Tomahawk Baseline Improvement Plan (TBIP)	Capability 2000
* Standoff Land Attack Missile expanded response (SLAM-ER)	Capability 1997
* Army Tactical Missile System (ATACMS)	Capability 1998

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II. WE CAN'T GET THERE FROM HERE

Peacetime target lists that are developed for specific areas of responsibilities (AOR) are composed of generic targets (i.e. military installations or facilities) with target reference points that equate to the center of mass for that target. These coordinates, although acceptable for small structures, are not adequate for precise targeting of large facilities where more precision is needed to satisfy the mission objectives. For instance, it is no longer militarily or politically feasible to simply strike the center of a enemy

installation when it is located within civilian areas. If intelligence indicates that the West-wing of building 'X' contains the communication node objective, but the East-wing is adjacent to a hospital, then precision targeting becomes paramount. Based on the World demographic trends, the Navy and Marine Corps of the future expect to project forces from the sea into densely populated littoral regions.¹² Enhanced accuracy in conjunction with the most current targeting imagery will be essential in reducing the collateral damage of preparatory and supporting fires in populated regions.

A. PRESENT PROCESS

NIMA's support to targeting takes a dual approach. The primary approach uses satellite imagery which is triangulated and packaged in 60 nautical mile by 60 nautical mile 'rectangles' that are referred to as Point Positioning Data Bases (PPDB). Currently in digital format, these databases are distributed to Joint and service target-planning sites world-wide where on-site coordinate mensuration occurs. In the absence of a PPDB, NIMA can be called upon to use a secondary approach where it derives point target coordinates using a manual process of limited throughput.

Imagery Acceptance:

The PPDB generation process begins when NIMA accepts the down-linked satellite imagery. Once NIMA determines that all imagery for a rectangle meets the cloud-free requirements and all stereo-models have been collected, it then becomes available for triangulation. The availability of a 'rectangle' for further processing is dependent upon the successful and acceptable completion of all images within the assigned rectangle boundaries, and it is therefore complicated by adverse weather conditions. Some

rectangles may not complete collection for months or years because of regional overcast conditions while rectangles in other geographic regions become available for production relatively quickly.

In numerous instances, a rectangle may be 90% complete but will not be made available for targeting simply because a few remaining images are too cloudy. This points to an imagery management system that is slowed significantly by the desire to satisfy cloud acceptance criteria for an entire rectangle rather than make acceptable images immediately available. Completion criteria are often relaxed in times of crisis, however such an approach still causes delays since further processing (triangulation) is required before a PPDB can be readied for exploitation.

Triangulation:

All image-based products produced by NIMA initially undergo a triangulation process that refines the raw ephemeris (position and attitude) information for each of the images covering a particular rectangle. The triangulation process provides internal and external NIMA customers with the relative and absolute accuracy needed to produce planning, precise navigation, target identification, and positioning and gunfire support products.

NIMA's approach to triangulation is based upon a comparison of expected to observed changes in camera ephemeris data following a mathematical (least squares) adjustment of all images within a rectangle. No ground points of known position (control points) assist in the triangulation process. In essence, the computer generated accuracy is verified strictly by a relative comparison of one group of stereo-images to another. This strategy has worked well in continental regions, but is problematic for small, isolated

islands where the few images needed to cover the landmass have no adjacent rectangles to validate their computed positions.

If indeed, ground control points were available, triangulation would change from **intersection** - on a rectangle comparison basis, to **resection** - on an image controled basis (see Appendix A). Such a change in methodology would be just as accurate as a comparison of predicted to actual camera movement between photos. The packaging of imagery into rectangles would become obsolete allowing for the rapid assembly of a global 'Grid' of acceptable and triangulated satellite imagery.

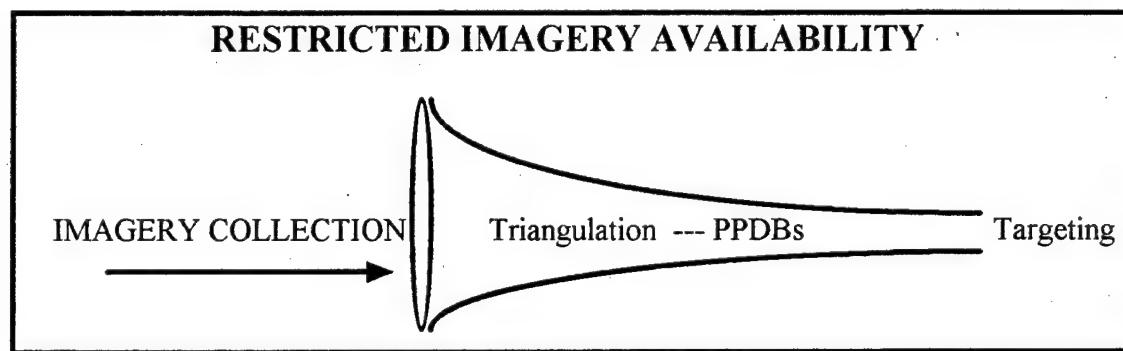
B. PRESENT CAPABILITIES

The Point Positioning Data Base (PPDB) is the premiere product now and in the future for the planning of PGM missions.¹³ Composed of triangulated satellite imagery, segments may be viewed at a softcopy workstation in three-dimensions; this allows for precise latitude, longitude and elevation measurements. With standard stereo techniques, reconnaissance imagery can be exploited in conjunction with the PPDB photo-pairs to locate targets not originally visible.¹⁴ Additional applications include the generation of precision elevation profiles and vertical obstruction data for very low altitude terminal maneuvers.

There are currently 2000 PPDBs available in digital format covering major areas of concern in the World. Yet, even excluding the polar regions, coverage presently consists of a small percentage of the Earth's surface, especially in cloudy regions. Where PPDBs are lacking, targeting elements, such as those within the Joint Intelligence Centers (JIC) currently rely on NIMA to generate impact point coordinates using a manual mensuration

process in conjunction with a triangulated rectangle.

NIMA presently triangulates approximately 2000 60X60 nautical mile rectangles per year, storing this data for subsequent PPDB production. However, the number of rectangles triangulated each year consistently falls short of annual imagery collection. This is so much so that now multiple years worth of useable data awaits exploitation. Such a 'stock-pile' of imagery is perishable. Time erodes the applicability of any intelligence source and none more than imagery. In 1998, the 2000th digital PPDB was produced out of 5500 PPDBs required for world-wide coverage for present areas of concern.¹⁵ It is evident that PPDB production has not kept pace with triangulation and triangulation in turn, has not kept pace with imagery collection. We are therefore managing a constricting imagery pipe-line from source receipt to targeting product.



At the present rate of PPDB production, NIMA will be able to satisfy a World-Wide requirement for positioning imagery by 2010. However, the currency of the imagery by that time will range from 1 to 10 years old. The mean age of satellite collection as of 1998 was five years old and growing.¹⁶

Will an ever-aging product be relevant in a future crisis? The present targeting approach calls for up-to-the-minute reconnaissance to be used in conjunction with the

PPDB while NIMA's long-term vision calls for programmed maintenance with new collection. The technical feasibility of reconnaissance has been long documented, while the practical considerations of time, weather, light and enemy denial, deception and defense during a true crisis are often glossed over. In addition, the plan for periodic maintenance admits an inherent reliance on the most current imagery. In the absence of recent reconnaissance images, the usefulness of a dated PPDB degrades rapidly and places a special emphasis on our ability to use the most recent collection in real-time.

In the near future, exponential growth in developing countries will further refine our definition of currency. The ability to quickly derive multiple geographic target coordinates that are both accurate and current from a single source are the keys to future precision engagement. Past conflicts have demonstrated that ultimate victory is integrally tied to the sustainment of fighting power. Likewise, an increasing reliance on PGMs and Global Positioning System Guided Munitions (GGMs) will define our culmination as that point at which targeting can no longer feed the weapon systems resulting in a loss of standoff firepower, operational tempo, and initiative.

C. NIMA's KEY ROLE

In a crisis in 1999, the demand for target coordinates for specific aim-points could exceed the capability of targeteers to manually select aim-points and NIMA's ability to produce them. Without a change in methodology, this disconnect between supply and demand is unlikely to go away.

The amount of total imagery available is currently restricted by satellite imagery acceptance, triangulation, and subsequent PPDB production procedures that must

evolve if NIMA is to fulfill its mission as an information provider. In times of crisis, a special request to release images from partially collected rectangles requires a Source Analyst status search, followed by shipment to the designated NIMA production site, triangulation, and PPDB production. In the past, such scenarios have been repeated many times for individual rectangles supporting crisis operations, but not without a complete disruption of planned production. Nima must be prepared to support two MRCs within 48 hours using multiple rectangle-sized image-sets that have not fully completed collection.

III. RECOMMENDATIONS: A NEW APPROACH TO IMAGERY MANAGEMENT

A. NIMA

Substantial changes need to be made if future precision targeting demands are to be met successfully. The current management process is wedded to the completion of 'boxes' of imagery rather than immediate availability of acceptable collection. In addition, the triangulation and targeting database production consistently falls short of total imagery collected annually. In the future, satellite imaging systems will undoubtedly surpass present collection capacity by several orders of magnitude.¹⁷ To cope with all this effectively, we need to restructure the end-to-end imagery management process to fully exploit emerging technologies so that they may be translated into battlespace dominance by 2010.

The framework for the inclusion of control points into the triangulation process currently exists. As of early 1999, a portion of all imagery down-loaded to the ground station was tested and evaluated against known ground positions. A modified

triangulation approach (**resection**), combined with a more robust evaluation procedure as imagery is received, would save both time and precious work-years.

A new and combined approach would see a move away from the rectangle completion strategy to a stereo-model processing strategy. As imagery is collected it would be evaluated on the same criteria as today; the difference is, if found acceptable, it would be made immediately available. The database of known ground points that is currently used to evaluate a fraction of the daily collection would be enhanced by on-going point surveys both internal and external to NIMA. A robust database of known control points would quickly evolve allowing for the immediate resection (control) of photo-pairs upon collection.

The technology currently exists for the automatic selection and mensuration of tie-points between photos. This coupled with control points of known position and accuracy could be used to perform a nearly autonomous triangulation, requiring minimal human intervention. As images are down-loaded, the corner coordinates associated with each (part of the MC&G data) would be compared with control holdings. The available control points would be automatically registered to the imagery and adjusted, if necessary, by operators to their exact locations. Tie point selection and triangulation of the down-loaded image set would then be performed automatically with the final results being evaluated by a geographical difference program (GEODIFF) that compares control coordinates to final computed coordinates. Only significant deviations would require human intervention.

The suggested scenario would then unfold quite differently than today. Imagery would be accepted, evaluated and triangulated immediately upon receipt. Its relationship

to adjacent imagery collection would no longer be a consideration, since rectangle packaging would be a thing of the past. Whether it be two images or twenty, the day's take for a particular region would be immediately processed. It would then be loaded to a NIMA library which would be available for all targeting customers to access through common gateway servers. Customers would search the library for images based on geographic area (corner coordinates) rather than by the present rectangle designations that remain foreign to those outside NIMA. In addition, targeting customers will have the flexibility to combine imagery into datasets of their own choosing.

As in the planning of PGM missions, this ability to choose specific image-sets becomes particularly advantageous in the elimination of vertical differences (shear) between adjacent models. At present, Y-parallax and shear are modeled (not eliminated) between image-pairs, strictly within a rectangle during the triangulation process. PGM planners must therefore rely on approximations of shear when flight-paths traverse several rectangles. Since these approximations are based on corresponding rectangle accuracy rather than an image-to-image comparison, PGM altitude deviations may exceed specifications. A model-based geopositioning process would eliminate this possibility by allowing vertical image-to-image differences to be calculated for any combination of images.

Shear and Y-parallax modeling would become subsequent operations performed at either NIMA or Joint Intelligence Targeting Centers through enhanced software tools. This philosophy supports the NIMA Feature Foundation Data Concept by providing for a complete set of imagery and data that can be enhanced and refined based on mission specific requirements. In addition, this concept supports the NIMA Points Program

Vision by allowing NIMA to become a service unit vice production unit.¹⁸ No 'stockpile' of accepted but aging imagery would exist as triangulation and evaluation would occur immediately upon acceptance at the ground station. Such a strategy would support the expected increase in collection capacity circa 2005. It may even be argued that the requirement for Point Positioning Data Base (PPDB) production would cease to exist. The imagery holdings within the NIMA library would themselves serve as the most current database of imagery that could be used for targeting on a moments notice.

B. Central Point Targeting Office

In the future NIMA needs to provide and maintain a NIMA Point Target / Intelligence database with service to Co-producers and customers. A Co-producer would be any command targeting office certified to place their data into the NIMA targeting layer of a National database. The best solution for ensuring the entire imagery system will be effective and run smoothly would be the creation of a Central Point Targeting Office. As a service unit, the targeting group within NIMA would evolve into the Central Point Targeting Office with national responsibilities for coordination of standards, inclusion of precise targeting information in the NIMA targeting layer, and certification of commercial off-the-shelf (imagery exploitation) software packages.¹⁹

The future NIMA database is envisioned to contain layers of geospatial, imagery, and imagery intelligence data and operate as part of the United States Imagery and Geospatial System (USIGS). Superior knowledge of mission space would be achieved through a more responsive information acquisition and production strategy, improved information management, easier access and delivery mechanisms, and more robust

application tools.

The envisioned capabilities of the Central Point Targeting Office in 2010 would start with the ability to ingest all types of imagery to include multi-spectral, infrared, synthetic aperture radar (SAR), hyper-spectral and accurate commercial imagery.²⁰ Non-MC&G photos would be registered to adjusted satellite imagery through the ability to read and translate multiple data formats. All workstations would be networked together and high capacity communication lines would allow for rapid customer access to information. Change detection software would allow for the immediate validation of image currency with respect to the customer defined mission. The ability to read many different database formats would foster complete synergy with service co-producers until a standardized format could be universally adopted.

The described capabilities would ensure that all imagery contains a geospatial support package allowing for immediate targeting. The all-source imagery could be retrieved from a central library via a geospatial workstation that would allow for point-and click target mensuration.²¹ One possible scenario envisions a JIC requesting imagery, performing mensuration, and sending the information to a NIMA database for storage. Before storage, the captured target information would be verified automatically for format and the actual point would be checked for duplication. Customer queries for imagery would trigger a search of the target database to see if the point has already been mensurated. If the point met the desired accuracy and currency, they would be provided with the information available.

A more likely scenario for the immediate future (1999-2004) would allow for the continued production of a majority of crisis targeting points within NIMA or the Cruise

Missile Planning Office. The bandwidth for complete imagery 'pull' from a NIMA library does not currently exist and may not ever be technically feasible for all forward targeting units. In addition, the expertise for the development of correct target location error (TLE) will always reside within NIMA, but is subject to rotation and the training level of individual service units.

The solution to these problems is to allow for continued and increased mensuration of aim points in a centralized location with joint connectivity. The NIMA Point Targeting Office could become a hub for geo-location that would bring together experts from all services and civilian support sectors. The knowledge base of photogrammetric and targeting experts would become centralized, synergistic, and team oriented. Rather than many targeteers dispersed across the globe, all questions concerning source, datum, grids and accuracy could be addressed communally and resolved jointly.

In this scenario, it would become unnecessary for JICs and JACs to pull entire images for targeting. A narrative description, reconnaissance image, or annotated map could be sent to NIMA which could in turn quickly deliver a set of numbered coordinates only. The Point Targeting Office within NIMA would have total control over points database integrity and targeting imagery dissemination would be restricted in house rather than world-wide distribution. In times of crisis, redundant requests would be filtered, joint service coordination would be enhanced and communication bandwidth requirements would be reduced.

IV. CONCLUSION

Clausewitz recognized that no plan survives the opening battle because the very

nature of interaction is bound to make war unpredictable.²² So too, we should recognize that future wars will be fast, deadly, and uncalculable. We are no longer safe in saying that we have multiple target-sets ready for the next war. Possible operational objectives and the enemy's reaction to them exceed our ability to pre-plan all targets. It is imperative then that we make the most current imagery available in near real-time for targeting.

This can be accomplished by restructuring the imagery acceptance and triangulation process. Acceptable imagery will be triangulated upon receipt and immediately placed into a NIMA library, accessible to targeting elements. The packaging of imagery into rectangles and 'shelving' for further processing will become a thing of the past. No backlog of uncompleted or un-triangulated rectangles would exist. Such a scenario would easily handle today's collection rates and provide for a smooth transition for future collection systems with increased capacity.

If a Central Point Targeting Office is created, it could act as the coordinator (broker) for all point targeting information within the NIMA library. High-volume communication lines, including the commercial Global Broadcast System (GBS) would be used to relay digital imagery of all types from any imagery library within the USIGS framework to any of the Co-producers within the defense community. Imagery would be available through the NIMA libraries directly, based on the real-time download of adjusted images and their ephemeris package. The customer would be able to request information from the database by coordinates, circular/rectangular area, installation name, city, or any combination of fields in the database.

Such a framework for geospatial information will help the defense and intelligence

communities to achieve JV2010. The increased accuracy, currency and availability of imagery (via immediate processing) as outlined previously, will serve as the foundation for all geospatial information needed to support Dominate Maneuver, Precision Engagement and Full Dimension Protection.

The preceding description portrays a prospective management system that makes the most current imagery available and accessible for targeting in near real-time. The design of enhanced capacity collectors does little to advance targeting if the imagery management practices of today remain unchanged. A "Grid" of targeting and intelligence imagery must be populated and maintained that will allow for the two precepts of Network Centric Warfare; **speed of access and availability**, to rapidly become a reality.²³

NOTES

¹ National Imagery and Mapping Agency (NIMA), Geospatial Information Infrastructure Master Plan: Volume I, (Fairfax, Va.: NIMA, 17 October 1997), p. 2-3.

² Chairman of the Joint Chiefs of Staff, Joint Vision 2010, Pentagon, Washington, D.C. undated, p. 16.

³ National Imagery and Mapping Agency (NIMA), Geospatial Information Infrastructure Master Plan: Volume I, (Fairfax, Va.: NIMA, 17 October 1997), p. 1-2.

⁴ Ibid, Volume II, p. 3-4.

⁵ The White House, National Science and Technology Council, National Space Policy, 19 September 1996, p. 7.

⁶ NIMA: GIA Reinvention Team Report to NIMA Deputy Director, June 1998.

⁷ "Precision Guided Munitions Investment Strategy", USAF White Paper, April 25, 1995, p. 13.

⁸ James R. Fitzsimonds, "The Coming Military Revolution" Parameters 25 (Summer 1995) : p. 30-36.

⁹ House of Representatives, Intelligence Community Act, Report of the Committee on National Security on H.R. 3237, 23 July 1996, Report 104-620, Part 2, p. 20.

¹⁰ House of Representatives, National Defense Authorization Act for Fiscal Year 1997, Conference Report to Accompany H.R. 3230, 30 July 1996, Report 104-724, p. 803.

¹¹ NIMA: Draft "Precise Geopositioning Orientation Course", p. 23.

¹² The United States Navy, Forward... From the Sea - The Navy Operational Concept, p. 2 <<http://www.chinfo.navy.mil/navpalib/policy/fromsea/ffseanoc.html>>

¹³ Lt. Col. Dick Wright, NIMA Customer Support Office, telephone conversation with author, 15 December 1998.

¹⁴ NIMA: Draft "Precise Geopositioning Orientation Course", Hardware and Software Systems Available for Target Mensuration, p. 13.

¹⁵ Lt. Col. Dick Wright, NIMA Customer Support Office, telephone conversation with author, 15 December 1998.

¹⁶ NIMA: GIA Reinvention Team Report to NIMA Deputy Director, June 1998.

¹⁷ David Taylor, "Emerging Satellite Imaging Capabilities and Its Impact on U.S. Military Operations.", Unpublished Research Paper, U.S. Naval War College, Newport, RI: 1998.

¹⁸ NIMA: "Point Target Vision for 2010", February 1998, p. 2.

¹⁹ Ibid, p. 4.

²⁰ Ibid, p. 6.

²¹ Ibid, p. 13

²² Carl Von Clausewitz, On War, edited and translated by Michael Howard and Peter Paret, (Princeton University Press, 1976, p. 139

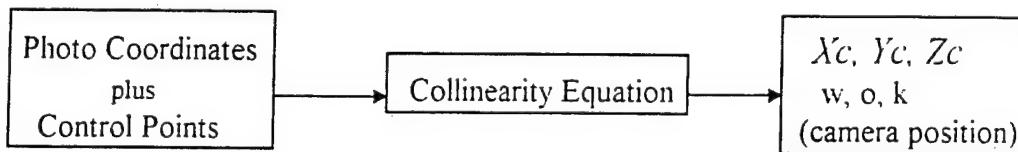
²³ Vice Admiral Cebrowski, Lecture to the Naval War College, Network Centric Warfare, Dec. 17, 1998.

APPENDIX A

TRIANGULATION METHODS :

1. **Resection** is the process that uses the collinearity equations (see Appendix B) to solve for the position and orientation of the camera at the moment of exposure for each image. Photo coordinates cannot be related to their respective ground coordinates unless the camera's precise position is known at the time of exposure. Resection will solve for the camera's Geocentric location (position) (X_c, Y_c, Z_c) and Roll, Tip and Yaw (Orientation) (w, o, k) through the knowledge of control point positions on the ground and measured photos. In order to satisfy the number of unknowns within the collinearity equations, the coordinates of known and identifiable ground control points on the images are required as input to a resection. Final camera position(s) verification is accomplished through a direct evaluation of computer generated, to known ground positions for all control points.

RESECTION PROCESS



Camera positions and orientations computed using known ground points (control), thus allowing for the subsequent mensuration of any point on the corresponding images.

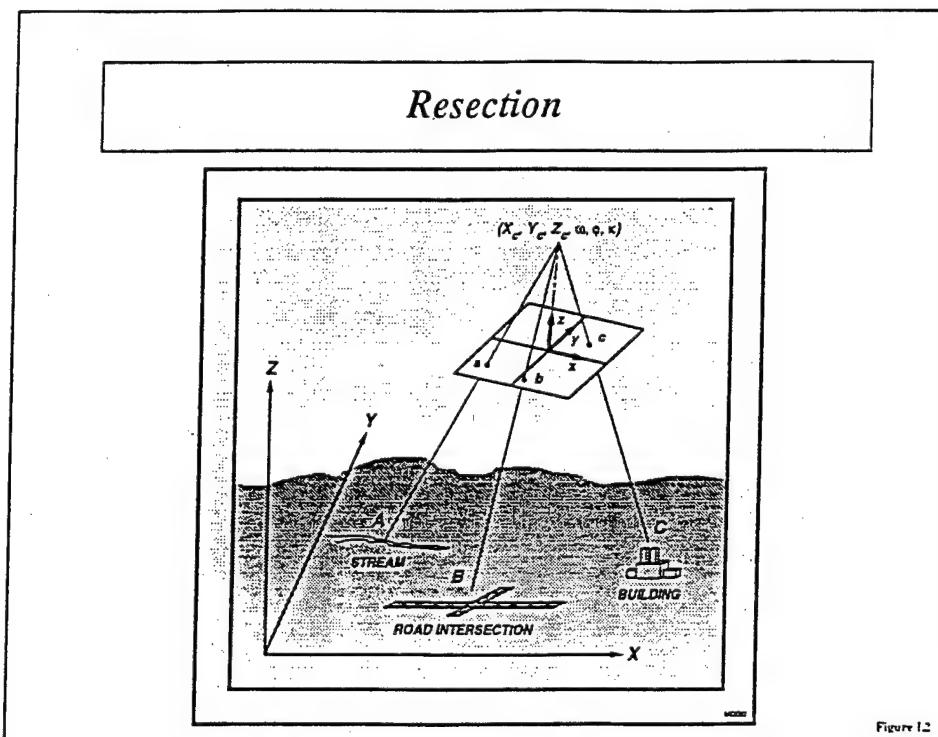
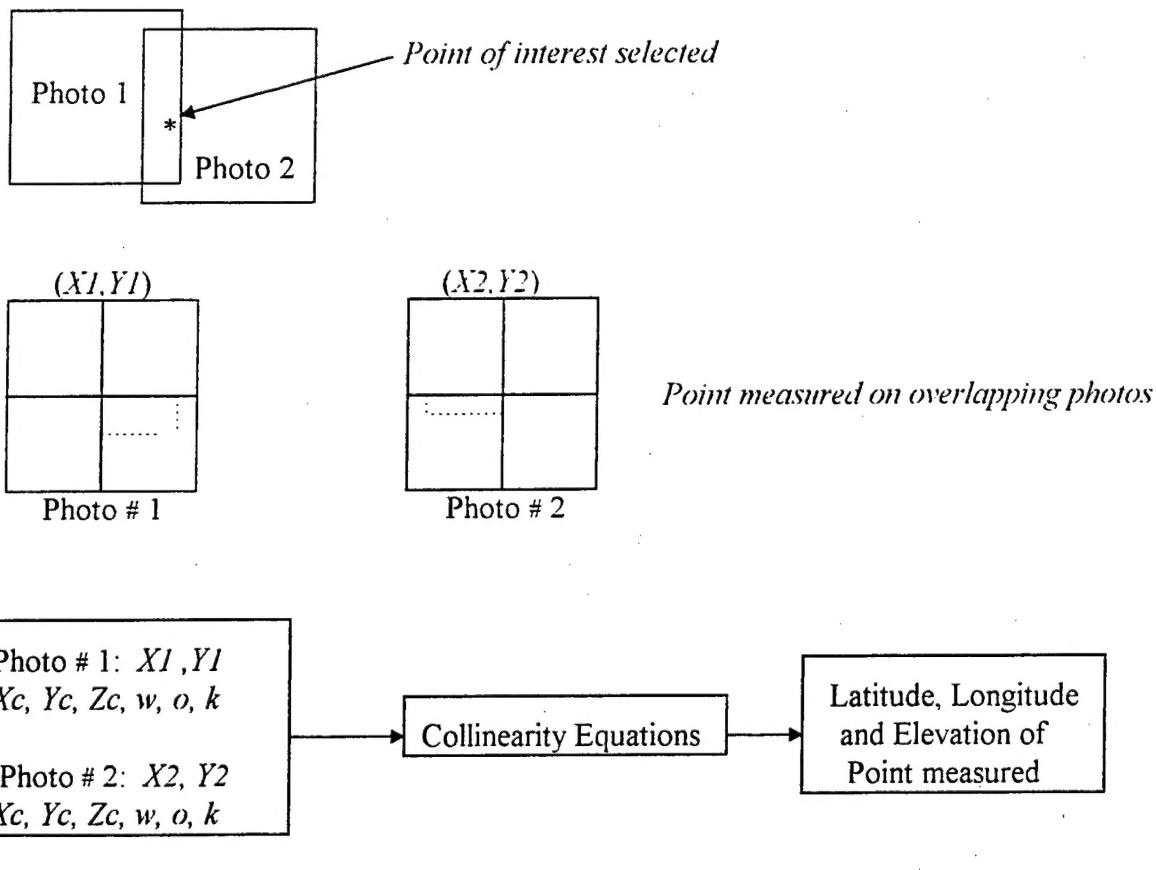


Figure 12

APPENDIX A

2. **Intersection** is performed using the corrected photo coordinates of tie-points between photos and initial estimates of the camera's position (X_c , Y_c , Z_c) and orientation (w, o, k) as known variables to the collinearity equation. This is a simultaneous adjustment that uses a least squares routine in the adjustment of the corrected photo coordinates, the estimated values of the camera position and orientation, and the estimated intersected values of the ground positions of all tie-points. The adjustment process computes corrections for the photo coordinates (PC), camera position (CP), camera orientation (OR), and ground position (GC). The corrections are analyzed to see if they meet a minimal change criteria. If they do not, the change is added to the initial estimate as input into the adjustment. If criteria is satisfied, the correction is added to the initial estimates and final refined camera positions, orientations and refined ground positions for measured points.

INTERSECTION METHOD



Intersection

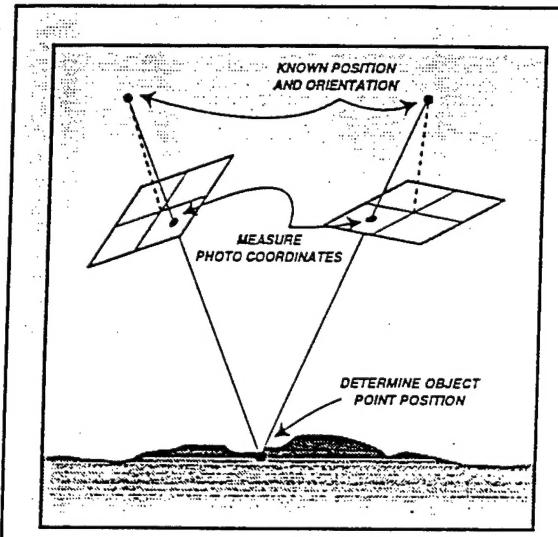
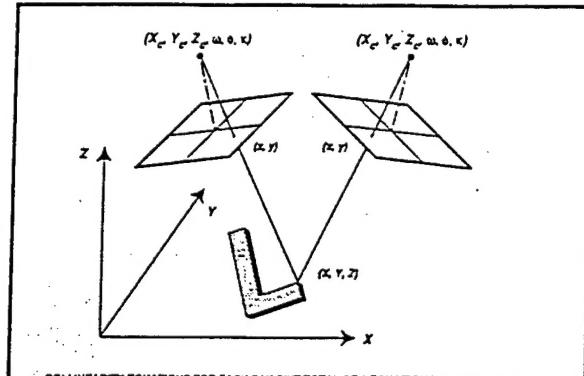


Figure H.6

Intersection



COLLINEARITY EQUATIONS FOR EACH RAY GIVE TOTAL OF 4 EQUATIONS IN 3 UNKNOWNs:

FOR LEFT RAY:

$$x = - \left[\begin{array}{l} M_{11}(X-X_c) + M_{12}(Y-Y_c) + M_{13}(Z-Z_c) \\ M_{31}(X-X_c) + M_{32}(Y-Y_c) + M_{33}(Z-Z_c) \end{array} \right] \quad z = - \left[\begin{array}{l} M_{11}(X-X_c) + M_{12}(Y-Y_c) + M_{13}(Z-Z_c) \\ M_{31}(X-X_c) + M_{32}(Y-Y_c) + M_{33}(Z-Z_c) \end{array} \right]$$

FOR RIGHT RAY:

$$y = - \left[\begin{array}{l} M_{21}(X-X_c) + M_{22}(Y-Y_c) + M_{23}(Z-Z_c) \\ M_{31}(X-X_c) + M_{32}(Y-Y_c) + M_{33}(Z-Z_c) \end{array} \right] \quad z = - \left[\begin{array}{l} M_{21}(X-X_c) + M_{22}(Y-Y_c) + M_{23}(Z-Z_c) \\ M_{31}(X-X_c) + M_{32}(Y-Y_c) + M_{33}(Z-Z_c) \end{array} \right]$$

Figure H.7

APPENDIX B

Collinearity:

The fundamental concept behind relating a point visible on the imagery to the location of the same point on the ground involves the principal of collinearity. Collinearity states that the point visible in the image, the exposure station of the camera, and the point on the ground lie along a single light-ray as shown in the diagram below.

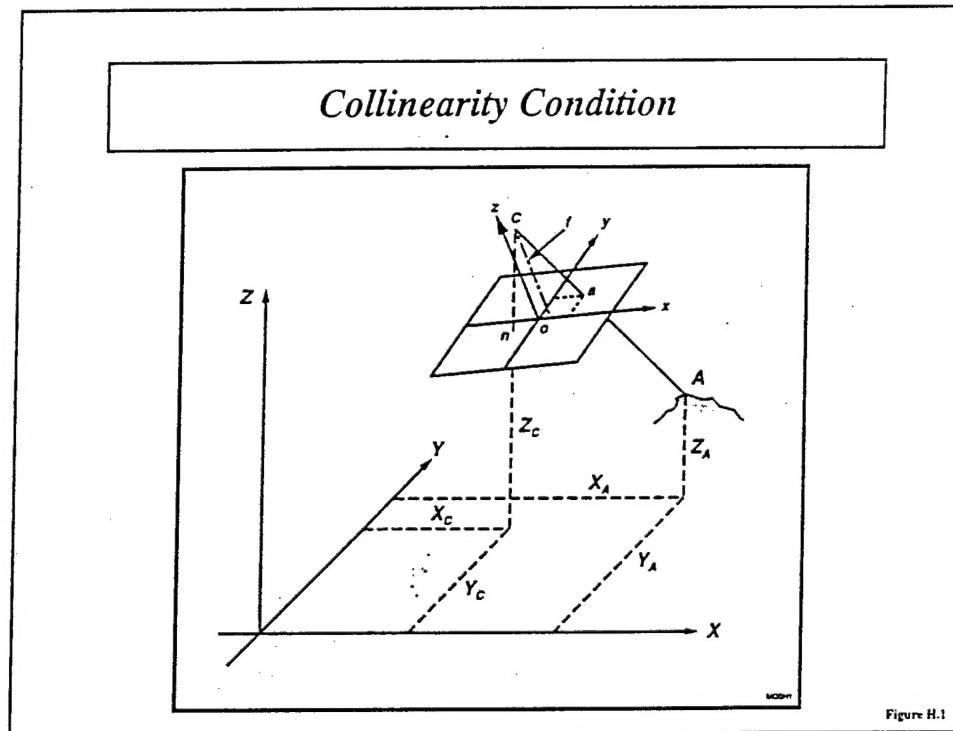


Figure H.1

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